

Leptonic and Hadronic Models for the Extra Components in Fermi-LAT GRBs

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Fermi satellite has detected extra spectral components in GeV energy range in several GRBs. Those components have power-law shapes, which may contribute to also X-ray band. The limited photon statistics make it difficult to determine the origin of GeV photons, namely internal or external shocks. We try to explain the extra components with our numerical simulations based on internal dissipation picture. Our leptonic model may reproduce not only the GeV excess via SSC emission but also the low-energy excess via the late synchrotron emission from remnant electrons. The hadronic models also reproduce keV-GeV power-law components by synchrotron and SSC emissions from secondary electron-positron pairs. In most cases the hadronic models require a much larger energy of protons than gamma-rays. However, the keV-GeV flat spectra detected in GRB 090902B is well explained with a comparable energy in protons and gamma-rays. Finally, we discuss both advantages and weaknesses for both the leptonic and hadronic models. To overcome difficulties in internal dissipation models, we propose introduction of continuous acceleration similar to the second-order Fermi acceleration.

I. EXTRA-SPECTRAL COMPONENTS

Most of the prompt emission spectra of gamma-ray bursts (GRBs) can be described by the well-known Band function [1]; the photon number spectrum $\propto \varepsilon^\alpha$ below ε_p , and $\propto \varepsilon^\beta$ above it. The spectral peak energy ε_p are usually seen in the MeV range. One of main scientific targets for the *Fermi* satellite was to investigate whether the spectral shape is consistent with the Band function even in the GeV band. The *Fermi* detected GeV photons from several very bright bursts ($E_{\text{iso}} > 10^{54}$ erg) such as GRB 080916C [2], GRB 090902B [3], and GRB 090926A [4]. In such bursts the onset of the GeV emission is delayed with respect to the MeV emission. Some of them also have an extra spectral component above a few GeV, distinct and additional to the usual Band function. Interestingly, GRB 090902B and GRB 090510 [5, 6] show a further, soft excess feature below ~ 20 keV, which is consistent with a continuation of the GeV power-law component. While such spectra may be explained by the early onset of the afterglow [7, 8], here we pursue possibility of internal-shock origins.

II. HADRONIC MODELS

If the spectral excesses in GeV and keV bands have the same origin, such a wide photon-energy range may imply the cascade emission due to hadrons. If the GRB accelerated ultra-high-energy protons, synchrotron and inverse Compton (IC) emission from an electron-positron pair cascade triggered by photopion interactions of the protons with low-energy photons [9–11] can reproduce power-law photon spectra as seen in *Fermi*-LAT GRBs. Through Monte Carlo simulations, Asano et al. [12] have shown that a proton luminosity much larger than gamma-ray luminosity is required to produce the extra spectral component in GRB 090510 as $L_p > 10^{55}$ erg s $^{-1}$ (see Fig.1). Namely, the efficiency of photopion production is very low. In this case, the spectrum of the GeV component is very hard with photon index ~ -1.6 , which requires a inverse Compton (IC) contribution from the secondary pairs. The prominent IC component leads to a weaker magnetic field. This entails a lower maximum energy of protons, and hence lower photopion production efficiency. Therefore, the required proton luminosity is so large in GRB 090510.

The assumed bulk Lorentz factor in Fig.1 is 1500, and the emission radius is $R = 10^{14}$ cm. If we adopt a smaller value of Γ , the pion production efficiency

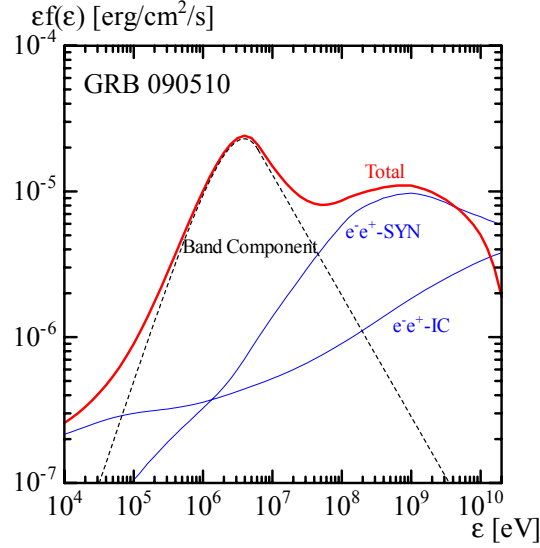


FIG. 1: Simulated spectra with hadronic models for GRB 090510. The assumed fraction of the magnetic energy density to the Band component photons is 10^{-3} , and the required proton luminosity is 200 times the luminosity of the Band component.

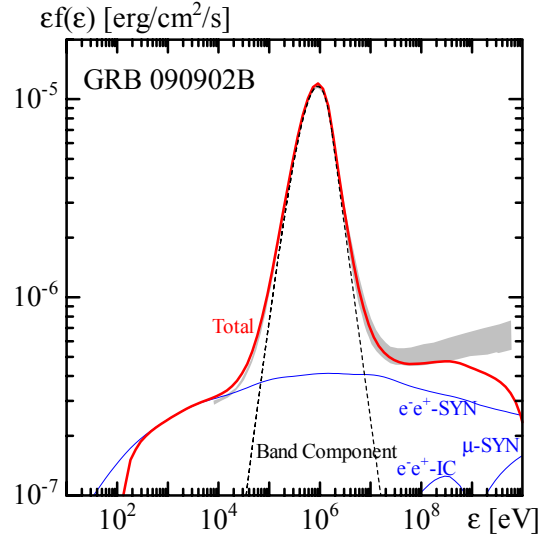


FIG. 2: Simulated spectra with hadronic models for GRB 090902B. The assumed fraction of the magnetic energy density to the Band component photons is 1.0, and the required proton luminosity is 3 times the luminosities of the Band component.

would increase as $t_{\text{exp}}/t_{\pi} \propto R^{-1}\Gamma^{-2}$. However, we should note that there is a lower limit to Γ , which is required to make the source optically thin to GeV photons. Given the photon luminosity and spectral shape, this minimum Lorentz factor can be estimated as shown in the online supporting materials in Abdo et al. (2009) [2]. In order to lower Γ , we have to increase the emission radius R . The lower limit of the Lorentz factor $\propto R^{1/(\beta-3)}$ does not decrease drastically (since $\beta \simeq -3$, $\Gamma_{\text{min}} \propto R^{-1/6}$). The required large luminosity is rather favorable for the GRB-UHECR scenario,

but it imposes stringent requirements on the energy budget of the central engine.

On the other hand, GRB 090902B is encouraging for the hadronic model because of its flat spectrum (photon index ~ -2) [13]. The Band component in this burst is an atypically narrow energy distribution as shown in Fig. 2, which may imply the photospheric emission [14]. The hadronic cascade emission can well reproduce the observed flat spectra including the soft excess feature below 50 keV (model parameters: $R = 10^{14}$ cm, $\Gamma = 1300$). Owing to the flat

spectral shape of the extra component, no IC component is required. We can adopt a strong magnetic field, which enhance the photomeson production efficiency. In this case the flux of the extra component is relatively low compared to the Band component, which also decreases the required proton luminosity. Therefore, the necessary nonthermal proton luminosity is then not excessive and only comparable to the Band component luminosity.

III. LEPTONIC MODELS

As Corsi et al. [15] discussed, the GeV emission may be due to IC emission from internal dissipation regions. However, it seems difficult to explain spectral excesses in both keV and GeV bands by IC emission. Recently, we carry out time-dependent simulations of photon emissions with leptonic models [16]. In our simulations, as the photon energy density increases with time because of synchrotron emission, the SSC component gradually grows and dominate the photon field later. This late growth of the IC component has been observed also in the simulations of Bošnjak et al. (2009) [17]. The resultant lightcurves show delayed onset of GeV emission, but the delay timescale would be within the approximate timescale of the keV-MeV pulse width. However, the longer delay compared to the pulse timescale such as observed in GRB 080916C is not explained by this effect only.

As shown in Fig. 3 (model parameters: $R = 6 \times 10^{15}$ cm, $\Gamma = 1000$, $B = 100$ G, $E_{\text{iso}} = 10^{54}$ erg, $\varepsilon_{\text{e,min}} = 11.3$ GeV), the model spectrum obtained from our simulations reproduce both the low and high energy excesses. When the magnetic field is weak enough, even at the end of the electron injection, the cooled electrons can be still relativistic. Such cooled electrons continue emitting synchrotron photons. The cooling due to IC gradually becomes inefficient as the seed photon density decreases. Such late synchrotron emission can yield the low-energy excess, while IC emission makes a GeV extra component.

Another possible model is the external IC emissions [18, 19], which can explain the delayed onset of GeV emission. The spatial separation between the source of the external photons and the site of the internal shock region corresponds to the delay timescale. We also carry out a simulation for this model assuming an external emission $L_{\text{seed}} = 10^{53}$ erg s $^{-1}$ with the Band function: $\varepsilon_{\text{peak}} \simeq 1$ MeV in the observer frame, $\alpha = -0.6$, and $\beta = -2.6$. The parameters for the internal shock are similar to those in Fig.3 as $R = 6 \times 10^{15}$ cm, $\Gamma = 1000$, $B = 100$ G, $E_{\text{iso}} = 3 \times 10^{53}$ erg, except for $\varepsilon_{\text{e,min}} = 50.6$ MeV. Our simulation reproduces the delayed onset of GeV emission, GeV extra component, and softening of the Band component. Since the external photon field in the rest frame of the emission region is highly anisotropic, the marginally

high-latitude emission contributes the most to the flux. Thus, the simulated GeV lightcurve shows larger delayed onset and longer tail than that in the usual leptonic models (Fig.4).

IV. IMPLICATION

The hadronic models usually require a much larger energy of protons than observed gamma-rays except for some examples such as GRB 090902B. Some may consider that the leptonic SSC models seem rather reasonable to reproduce both the GeV and keV excesses. However, a lower magnetic field and high Lorentz factor, required to make an optically thin source for GeV photons generated via IC emission, leads to a very high minimum Lorentz factor ($\gamma_{\text{e,min}} \sim 10^4$) for random motion of accelerated electrons. If all electrons are accelerated in internal shock regions, such a high value may be impossible. Thus, the fraction of accelerated electrons should be small in leptonic models to explain *Fermi*-LAT GRBs.

On the contrary, the minimum Lorentz factor of electrons $\gamma_{\text{e,min}}$ in the external IC model should be small to adjust the energy of scattered photons. Given the total energy, such small $\gamma_{\text{e,min}}$ means large number of electrons. If the numbers of electrons and protons are the same, the proton energy becomes fairly large ($\sim 1.9 \times 10^{54}$ erg in the case of Fig.4, while the luminosity of the Band component $L_{\text{seed}} = 10^{53}$ erg s $^{-1}$). To enhance the emission efficiency, electron-positron plasma should be introduced in such models.

Despite the ability of our straightforward simulations to reproduce various observed properties of the GRB prompt emission, the discrepancy with the low-energy index α remains unexplained. The injected electrons cool via synchrotron radiation, and distribute below $\gamma_{\text{e,min}}$ with a power-law index -2 . The resultant photon index becomes $\alpha \sim -1.5$, while the observed typical values are -1.0 or harder. The low-energy photon index affects the photomeson production efficiency. We have also tried to resolve this problem [20, 21] considering continuous acceleration/heating due to magnetic turbulences induced via various types of instabilities such as Richtmyer-Meshkov instability [22]. The acceleration/heating balances with the synchrotron cooling, so the observed low-energy spectral index is naturally explained. Such effect should be included in the time-dependent code to reproduce the global shape of the GRB prompt spectra from eV to GeV. Especially, electron injection due to hadronic processes and succeeding acceleration by turbulences may explain very high $\gamma_{\text{e,min}}$ and GeV emission.

We plan to develop the time-dependent code shown here to treat hadronic processes or continuous acceleration/heating. Note that the results for the hadronic models shown here were calculated based on

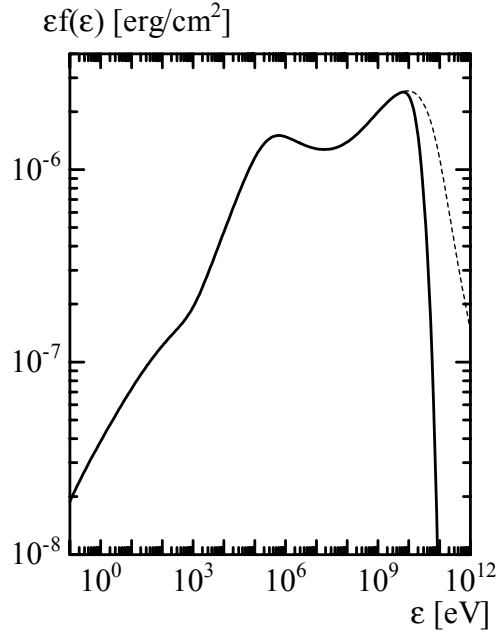


FIG. 3: The SSC-model fluence obtained from our time-dependent simulation (assuming $z = 1$). The dashed line neglects absorption due to EBL.

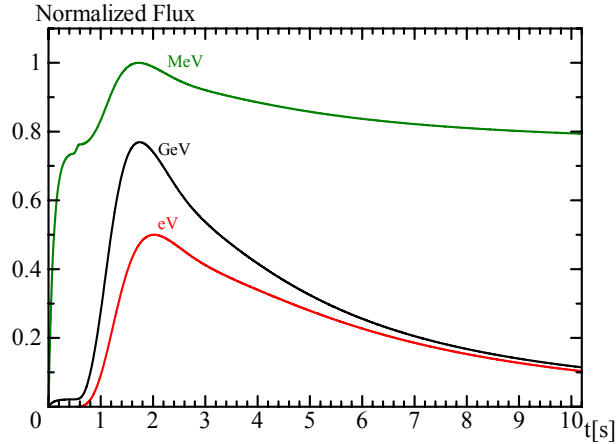


FIG. 4: The lightcurves for the external IC model. In the MeV band the external photons from inside region dominate, while GeV and eV emissions are originated from accelerated electrons in outside dissipation region.

the steady state approximation. We will carry out simulations for various situations involving dissipative photospheres and internal or external dissipation or shock regions. Moreover, the code will be useful for simulating emissions of other high-energy sources, such as active galactic nuclei, supernova remnant, and clusters of galaxies.

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